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Waste-heat recovery potential in Turkish textile industry: Case study for city of Bursa

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Abstract

Textile sector of Turkey has a large production capacity and it is one of the important sectors. Many industrial heating processes generate waste energy in textile industry. Therefore, there is a tremendous waste-heat potential to utilize in textile applications. This study assesses the potential of waste-heat obtained from particularly dyeing process at textile industry in Bursa where textile center of Turkey. Energy consumptions could be decreased by using of waste-heat recovery systems (WHRSs). A thermodynamic analysis is performed in this study. An exergy-based approach is performed for optimizing the effective working conditions for WHRSs with water-to-water shell and tube heat exchanger. The payback period is found to be less than 6 months. The variations of the parameters which affect the system performance such as waste-water inlet temperature, mass flow rate, cooling water inlet pressure and dead state conditions are examined respectively. The results of the analysis show that the exergy destruction rate and economical profit increase with increasing of mass flow rate of the waste water. Similarly, exergy destruction rate, effectiveness and economical profit increase while the second law efficiency decreases as the waste-water inlet temperature increases.

Keywords: Waste-heat recovery; Energy analysis; Exergy analysis; Economical analysis

Contents

1. Introduction

Turkey is an energy importing country which over half of energy requirements met by imported fuels (natural-gas, oil, coal, etc.). For this reason, utilization of WHRSs seems to be a key concept for clean and sustainable future for the country. The investigations have been directed to technology development in the usage of waste-heat sources as a result of ever increasing in the Turkish energy demand associated with environmental factors.

Bursa is an industrialized city where is located in the north-west of Turkey in the Marmara Region, 40.18°N, 29.07°E, 150 m altitude. Bursa is one of the fourth biggest city in Turkey and has an important share of energy consumption. There are many factors that have made city of Bursa into an important center succeeding Istanbul, factors such as the passage through Bursa of all routes connecting the Marmara Region to Aegean Region, the city being particularly the center of the country's textile and automotive industry, the connection of agricultural production subsequently the development of the transport

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Nomenclature

a	discount rate
A_s	heat transfer surface area (m^2)
B	benefit
C	cost
d	diameter (m)
e	specific exergy (kJ/kg)
$\dot{E}$	exergy rate (kW)
EP	economical profit ($)
F	the correction factor for multi-pass heat exchangers
h	specific enthalpy (kJ/kg)
i	interest rate
$\dot{I}$	exergy destruction (kW)
L	the length of the tube (m)
$\dot{m}$	mass flow rate (kg/s)
n	number of tube
NGP	natural-gas price ($/$m^3$)
NPV	net present value
p	period
P	pressure (kPa)
ΔP_t	pressure drop (kPa)
$\dot{Q}$	the heat transfer rate (kW)
s	specific entropy (kJ/(kg K))
T	temperature (K)
TP	number of tube-passes
ΔT_{lm}	log-mean temperature difference (°C)
u	velocity (m/s)
U	overall heat transfer coefficient (kW/(m^2 K))

Greek letters

ε	effectiveness
η	efficiency (%)
ρ	density (kg/m^3)

Subscripts

cw	cooling water
in	inlet
II	second law
o	dead state conditions
out	outlet
ww	waste water

Superscripts

.	quantity per unit time
-	average value

industry, and finally the historical and touristy assets of the city. Automotive and textile are the dominant sectors in Bursa which has seven organized industrial district. Seventy-five percentage of the total production capacity of synthetic yarn in Turkey is covered by Bursa textile sector and the total employees are approximately 60,000 in this sector. At least 25% of dyeing industry in Turkey is also located in Bursa. The competition of textile sector is very active in the world but the share of waste-heat used in Bursa is, however, only about 10%. Therefore, comprehensive performance evaluation is essential for waste-heat resources in the textile industry. For this reason, the intensive research and development studies have been carried out for effective and economical utilization of WHRSs. The increase in energy cost has required more effective use of energy and recovering the lost energy are of great importance for textile processes.

Effective utilization of lost energy in industry is important economically and environmentally not only for Turkey but also for all over the world. Designing efficient and cost effective systems that also meet lower capital and running costs and environmental conditions are the foremost challenges that engineers face. In the world, with finite natural resources and large energy demands, it becomes ever increasingly important to understand the mechanisms that degrade energy and resources and to develop systematic approaches for improving systems and, thus, also reducing the impact on the environment. So, waste-heat recovery systems have been investigated by numerous researchers.

Finishing accounts for a sizeable share of the total amount of energy is consumed by the textile industry. While considerable progress has been made in most wet treatment processes as regards saving and recovering energy, much still remains to be done in this respect in drying and in treatments involving the use of hot air (e.g. heat setting, polymerization, etc.). This study focuses on heat recovery from hot air or hot water coming from dryers, polymerization machines, coating systems for recycling heat is also discussed [1].

Large volumes of heated water are presently being used in textile mills for rinsing in the desizing, scouring, and bleaching steps of continuous preparation ranges. Much of the hot process water and some of the chemicals that are presently being discharged as waste can be recovered and reused at a significant cost savings [2].

A large number of different techniques for recovering waste heat which can be reduce process operation cost and conserve significant amount of fuel. Waste-heat recovery is likely to be the major conservation method to be adopted in a wide range of industries, and can involve a substantial outlay of capital [3].

Gas to gas waste-heat recovery exchangers may be categorized as plate-fin and primary surface exchangers, heat pipe exchangers, rotary regenerators, radiation and convection recuperators, and runaround coils. A metallic radiation recuperator consist of two concentric metal tubes with the hot exhaust (flue) gas flowing through the central duct and the air to be preheated flowing in the outer annulus [see Refs. 4,5].

Kaup [6] dealt with heat recovery from thermal effluents of textile finishing mills, notably in the connection with the so-called circulating drying processes. It is shown that the choice of a heat recovery system depends on the condition prevailing in individual mills. By proper application of such systems in textile finishing mills up to 60% of the waste heat can be recovered from effluents of pressure dryers.

A heat recovery is always dependent on the conditions prevailing in the respective mills which are influenced by the materials to be finished, the hot water consumption, the effluent

temperatures, etc. This article serve as an example for many installations of different manufacture that are offered all over the world today, is intended to be an incentive for assessment of individual solution to suit various conditions [6].

Naefe [7] pointed out by reference to a few actual case histories ways and means of saving energy, quoting the costs and likely benefits of new energy-saving technologies in textile dyeing and finishing.

In textile dyeing processes, bottle washing processes and in public baths, a large quantity of warm water, 293–323 K, is discharged but almost all of such water is discarded because the temperature is low. An attempt was made by Kannoh [8] to recover heat from waste water of dyeing process using a heat pump.

As conservation measures were undertaken for the production of cotton and cotton/polyester blend fabrics and as process by Witt and Johnston [9] control instrumentation became operational, the observation was made that the waste-water heat exchangers were underutilized. The idea was developed to use the excess capacity to heat boiler feedwater.

Many possibilities of conserving energy in textile finishing are not made use of, inspite of urgent appeals to conserve energy issued over a new lengthy period. Tischbein [10] offers a choice of examples for the many possibilities and aims at encouraging initiatives for energy conservation and cost reduction.

The major energy saving systems are as follows: (1) waste-water heat recovery; (2) condensing stack economizer; (3) wood gasification; (4) conventional or wood gasification cogeneration of electricity and steam; (5) wood gas for coater frame incineration; (6) air to air heat recovery; and (7) electrical savings. All seven areas apply to dyehouses in the category which is spending up over 750,000 annually on boiler fuel [11].

Process efficiency should be improved before considering waste-heat recovery from any stream or systems; Richlen [12] also describes five factors for the selection of waste-heat recovery exchangers: usability (of available waste heat), temperature, fouling, corrosion, characteristics (of the waste-heat stream), and quantity (flow rate of waste-heat stream and desired heat exchanger effectiveness).

A process to recover at least 80% of water, auxiliary chemicals and energy from effluents of textile dye-houses has been developed by Gaete and Fedele [13]. The water and the auxiliary chemicals can be reused by the textile industry to dye either light or dark shades. Energy is recovered in the form of hot water. The payback time for the process is between 18 and 30 months, depending upon the degree of automation. Moreover, this technology minimizes the discharge of pollutants contributing greatly to the solution of many environmental problems.

A case study in a textile factory which use of gas–turbine cogeneration with a post-combustion heat recovery system is found to be the most suitable solution by Tang and Mohanty [14]. This system has not only the highest thermal efficiency, but it can also provide flexibility in operation.

Bonilla et al. [15] presented technological recovery potential of waste-heat in the industry of Basque country and developed a methodology for eight heat recovery techniques.

The runaround coils are used in HVAC applications and drying applications. Kreith and West [16] have also been used in a number of industrial applications where high and low temperature fluids cannot be brought close together and the risk of mixing them should be minimized.

While the energy consuming process of drying paper, textiles and construction materials during manufacturing has warranted a large number of studies, the more dispersed everyday activity of laundry drying seems not to have awakened as much interest. This is perhaps because laundry drying installations are usually either domestic or comparatively small. In this study, it is demonstrated by Conde [17] that conventional tumbler dryer technology is susceptible to improvement by the use of heat recovery heat exchangers. The energy recovery potential may be as high as 20% of that required for heating the drying air.

Ogulata et al. [18] investigated a cross-flow plate-type air-to-air heat exchanger for waste-heat recovery systems. The exergy destruction of the heat exchanger was taken into consideration, while the design of the heat exchanger was such that the minimum entropy generation number was analyzed with respect to the second law of thermodynamics in the cross-flow heat exchanger.

An exergy optimization of a heat exchanger was carried out on the basis of the life cycle analysis method by Cornelissen and Hirs [19]. They concluded that the optimal design of a heat exchanger can be obtained by the combination of exergy analysis and life cycle analysis.

A thermo-economic optimization analysis was presented yielding simple algebraic formulas for estimating the optimum heat exchanger area for energy recovery applications by Soylemez [20].

A plate type heat exchanger designed and manufactured in laboratory conditions is presented by Ogulata and Doba Kadem [21]. Experimental results indicate the suitability of the exchanger in textile industry, especially in drying machines.

Hung [22] examined the waste-heat recovery potential of organic Rankine cycle (ORC) for low enthalpy heat sources. Exergy destruction rates for different fluids were calculated and compared for different turbine inlet pressure in ORC.

Various adsorption refrigeration cycles have been investigated by Wang [23], such as continuous heat recovery cycle, mass recovery cycle, thermal wave cycle, convective thermal wave cycle, cascade multi effect cycle, hybrid heating and cooling cycle, etc. Several prototype adsorption refrigeration systems have been developed and tested, typical examples are continuous heat regenerative adsorption ice maker using spiral plate adsorbers, adsorption heat pump using novel heat exchanger as adsorbers, solar powered adsorption ice maker, solar powered hybrid system of water heater and adsorption refrigerator, waste-heat driven air conditioning system for automobiles.

Dincer and Al-Muslim [24] investigated a reheat Rankine cycle steam power plant and stated that a full exergy analysis helps to identify the components where inefficiencies occur.

The principal reason for attempting to recover waste heat is economic. All waste heat that is successfully recovered directly

substitutes for purchased energy and therefore reduces the consumption of and the cost of that energy. A second potential benefit is realized when waste-heat substitution results in smaller capacity requirements for energy conversion equipment. Thus, the use of waste-heat recovery can reduce capital costs in new installations. The waste-heat recovery reduces the requirement for space-heating energy. This permits a reduction in the capacity of the furnaces or boilers used for heating the plant. In every case of waste-heat recovery, a gratuitous benefit is derived: that of reducing thermal pollution of the environment by an amount exactly equal to the energy recovered, at no direct cost to the recoverer [25].

In recent years, a great deal of attention is focussed on the efficient utilization of energy resources with minimum heat loss. There is a growing interest on second law analysis to minimize the entropy generation in various thermal units and thereby to improve and optimize the design and performance. In this study, a waste-heat recovery steam generator is considered which consists of an economizer, an evaporator and a super heater. The unit produces superheated steam by absorbing heat from the hot flue gases. A general equation for the entropy generation has been proposed, which incorporates all the irreversibilities associated with the process [26].

An energy optimization of production of a thermoplastic material, polyamid-6 i.e. nylon-6, using boiler flue gases heat recovery is presented by Mihelic-Bogdanic and Budin [27]. Energy and environmental studies show that in increase of process efficiency simultaneously with a decrease of thermal pollution. If the feed water is heated with flue gases, the fuel consumption is reduced by about 13%, while the boiler outlet flue gases temperature decreases from 232 to 55 °C. The combination of feed water and air preheating shows fuel savings of 13.6%, and the outlet flue gases temperature is reduced to 29.7 °C.

The relation is investigated between energetic and exergetic losses and capital costs for devices in modern coal-fired, oil-fired and nuclear electrical generating stations by Rosen and Dincer [28]. Söderman [29] investigated the possibilities for recovering energy from waste in Sweden around the year 2010.

Xuehu et al. [30] report the test results of the first industrial-scale absorption heat transformer (AHT) equipment in China, to recover the waste heat released from mixture of steam and organic vapor at 98 °C in coacervation section, synthetic rubber plant in China. The recovered heat is used to heat hot water from 95 to 110 °C, feeding back to the coagulator as the supplementary heating source.

Thermoelectric waste-heat recovery is investigated by Douglas and Gregory [31] for current thermoelectric materials with advanced heat exchangers. Numerical heat exchanger models integrated with models for Bi_2Te_3 thermoelectric modules are used in optimization studies of thermoelectric waste-heat recovery with air cooling in a cross flow heat exchanger. Power losses from an air fan and a fluid pump result in an optimal configuration at intermediate cooling air and hot fluid flows.

A series of cleaner production (CP) options related to water and energy conservation were investigated by Kiran-Ciliz [32] in a Turkish cotton-fabric producing company. She [32] carried out a technical and economical analysis for the reduction of water consumption in the regeneration process, water and chemical savings in the dyeing process, heat recovery from the blow-down which was discharged into the waste-water treatment plant, and heat recovery of process waste water.

Ogulata [33] presented a study for waste-heat recovery in textile drying processes. In this study, system parameters such as heater capacity, recuperator efficiency and energy saving potential were calculated as a function of dryer-inlet-temperature.

Building integrated photovoltaic (BiPV) systems generate electricity, but also heat, which is typically wasted and also reduces the efficiency of generation. A heat recovery unit can be combined with a BiPV system to take advantage of this waste heat, thus providing cogeneration. Two different photovoltaic (PV) cell types were combined with a heat recovery unit and analyzed in terms of their life-cycle energy consumption to determine the energy payback period [34].

The energy conservation and/or energy efficiency improvement is becoming vital energy issues in the country which imports fuel. Cogeneration system or combined heat and power system used for the utilization of waste heat from energy and industrial sectors is thus becoming attractive due to the energy, economic and environmental policies for pursuing stable electricity supply, sustainable development and environmental pollution mitigation in Taiwan. Wen-Tien and Kuo-Jung [35] presented an analysis of cogeneration system utilized as sustainable energy in the industrial sector in Taiwan.

Souza et al. [36] gave an efficient tool for industrial purpose, which give a quickly prediction when configuration changes are suggested by industrial engineers in the continuous washing process. Using the conservation balances, guaranteeing the global mass conservation, it is possible to obtain the total organic mass and water consumption in this new configuration and to compare with previous results to choose the best option for the process.

Characteristics of heat transfer equipment and/or heat exchangers used in waste to energy systems and their specific features are described and discussed by Stehlik [37]. A combination of intuitive design, know how and sophisticated approach based on up-to-date computational tools is shown. Concrete examples involve e.g. heat exchangers of heat recovery systems (especially air pre-heaters and heat recovery steam generators) of units for the thermal processing of wastes, their design, arrangement, optimisation, etc. An application of CFD (computational fluid dynamics) both for improved design and troubleshooting (e.g. elimination of fouling) is demonstrated.

Finally, discussing methods for maximizing available energy, energy conversion book [38] surveys the latest advances in energy conversion from a wide variety of currently available energy sources. The book describes energy sources such as fossil fuels, biomass including refuse-derived biomass fuels, nuclear, solar radiation, wind, geothermal and ocean, then provides the terminology and units used for each energy resource and their equivalence. The book also provides

comprehensive coverage of end use efficiency of green technology. It includes in-depth discussion not only of better efficient energy management in buildings and industry, but also of how to plan and design for efficient use and management from the ground up [38].

In the present study, an analysis based on exergy concept is carried out in order to find effective working conditions for WHRSs. The study describes an easy-to-follow procedure for energy and exergy analysis for WHRSs and how to apply the described procedure to assess the performance, exergy destruction and economical contribution, and thus showing the direction for improvement of WHRSs. The scope of this study is to present systematically the possibilities and the efficiencies of heat recovery from discharged-water form textile process. The variation of performance parameters of the system are also calculated an appropriate mathematical model which is based on the first and second-law of thermodynamics. A brief survey of heat recovery systems is also given.

2. Analysis

Wastewater is the largest waste stream for all sub-sectors of the textile industry [32]. There are several techniques for waste-heat recovery. The most common one is heat exchangers. Effectiveness, ε, is a measure of thermal performance of a heat exchanger. It is defined for a given heat exchanger of any flow arrangement as a ratio of the actual heat transfer rate from the hot fluid to the cold fluid to the maximum possible heat transfer rate $\dot{Q}_{\max}$ thermodynamically permitted.

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} \tag{1}$$

The rate of heat transfer in a heat exchanger can also be expressed in an analogous manner to Newton's law of cooling as

$$\dot{Q} = UA_{\rm s}\Delta T_{\rm lm}F \tag{2}$$

where U is the overall heat transfer coefficient, $A_{\rm s}$, is the heat transfer surface area, $\Delta T_{\rm lm}$ is the log-mean temperature difference and F is the correction factor for multi-pass heat exchangers. The length of the tube, L, can be calculated based on the heat transfer surface area, $A_{\rm s}$.

$$L = \frac{A_{\rm s}}{{\rm TP}\,n\pi d} \tag{3}$$

where n is the number of tube, TP is the number of tube-passes and d is the diameter of the tube.

The work potential of the energy contained in a system at a specified state is simply the maximum useful work that can be obtained from the system. This situation is described with the exergy term. In an exergy analysis, initial state is specified and it is not a variable. The system should be in the dead state at the end of the process to maximize the work output [39].

If a system is in a thermodynamic equilibrium with its surroundings, the system is called to be in the dead state. Therefore, it can be concluded that a system will deliver the maximum possible work as it undergoes a reversible process from the specified initial state to the state of its environment, i.e. the dead state. This represents the useful work potential of the system at the specified state and its called exergy (availability). The exergy of a quantity of energy or a matter is a measure of its usefulness or potential to cause change. Exergy appears to be an effective measure of the potential of a substance to impact the environment [40]. Exergy is an entirely different concept. It represents quantitatively the useful energy, or the ability to do or receive work-the work content-of the great variety of streams (mass, heat, work etc.) that flow through the system. The first attribute of the property exergy is that it makes it possible to compare on a common basis different interactions (inputs, outputs, work, heat, etc.) [41]. So, the exergy analysis is a powerful tool for the design, analysis and classification of thermal systems [42–44].

Tube side total pressure drop, $\Delta P_{\rm t}$, in the heat exchanger can be calculated from Eq. (4) as the sum of the local and the friction losses [45].

$$\Delta P_{\rm t} = {\rm TP}\,n\left[\lambda\frac{L}{d_{\rm i}} + 2.5\right]\frac{\rho\bar{u}_{\rm cw}^2}{2} \tag{4}$$

where λ is the friction coefficient which can be determined from Moody diagram, $d_{\rm i}$ is the inner diameter of the tube, ρ is the density of the cooling water, and $\bar{u}_{\rm cw}$ is the average velocity of cooling water.

Disregarding kinetic and potential energy changes, the specific flow exergy of fluid at any state, e, can be calculated from Eq. (5) [39–43].

$$e = h - h_{\rm o} - T_{\rm o}(s - s_{\rm o}) \tag{5}$$

where h is the specific enthalpy (kJ/kg), s is the specific entropy (kJ/(kg K)), T is the temperature (K) and o is the dead state conditions.

Multiplying specific exergy, e, by the mass flow rate of the fluid, $\dot{m}$, gives the exergy rate, $\dot{E}$, as

$$\dot{E} = \dot{m}e \tag{6}$$

The rate form of the entropy balance can be expressed as

$$\underbrace{\dot{S}_{\rm in} - \dot{S}_{\rm out}}_{\text{Net entropy transfer rate}} = \underbrace{\dot{S}_{\rm gen}}_{\text{Entropy generation rate}} \tag{7}$$

and the entropy generation rate, $\dot{S}_{\rm gen}$, can be calculated as

$$\dot{S}_{\rm gen} = \sum \dot{m}_{\rm out}s_{\rm out} - \sum \dot{m}_{\rm in}s_{\rm in} - \sum\frac{\dot{Q}}{T} \tag{8}$$

where $\dot{Q}$ is the heat transfer rate. Rate of exergy destruction (or the rate of irreversibility), $\dot{I}$, can be obtained based on the general exergy rate balance for steady-state open system as

$$\dot{I} = T_{\rm o}\dot{S}_{\rm gen} \tag{9}$$

where $T_{\rm o}$ is the temperature of dead state. The first law efficiency alone is not a realistic or consistent measure of performance for devices. Thus, a parameter is defined to express the performance of a device to the performance under reversible conditions for the same final states. This parameter is

called second law efficiency, η_{II} (or exergetic efficiency). Second law efficiency, η_{II}, of a heat exchanger can be calculated from Eq. (10) [46].

$$\eta_{II} = \frac{\dot{m}_{cw}(e_{cw,out} - e_{cw,in})}{\dot{m}_{ww}(e_{ww,in} - e_{ww,out})} \quad (10)$$

3. Case study

Process values which are presented in Table 1 are the average values of seven different dyeing plants over 205 active dyeing plants in Bursa. Economical evaluation and second law analysis are carried out for one of the plant that has eight dyeing units. The investigated process consists of eight steps of which are bleaching, washing, acidification, dyeing, cold rinsing, washing, hot rinsing and finishing. Governing parameters that are used for calculation of WHRSs are mass flow rate, temperature and process time, respectively.

Results of the used computer code for the case study and schematic illustration of the WHRS can be seen in Fig. 1. Heat exchanger, the main unit of WHRS, is especially investigated.

The following several assumptions are adopted for the first and second law analyses and economical evaluation.

1. All processes are steady state and steady flow with negligible potential and kinetic energy effects and no chemical reaction.
2. The direction of heat transfer to the system is positive.
3. The dead state conditions are taken as $T_o = 15$ °C and $P_o = 100$ kPa.
4. Cold rinsing and finishing steps are neglected because the processes has relatively low temperature. So, the waste-water volumetric flow rate is 30,000 L/one pass consignment.
5. One dyeing process is carried out in one shift of the plant. Dyeing plant has eight units and three shifts a day. The total volumetric flow rate of waste water is: $3 \times 8 \times 30{,}000 = 720{,}000$ L/day = 720 t/day.
6. Dyeing plant working period is accepted as 24 h/day and 300 day/year.
7. The cooling water inlet temperature, $T_{cw,in}$, is 20 °C and the cooling water outlet temperature, $T_{cw,out}$, is 60 °C for the needs of textile finishing processes.

Different dyeing steps have different process temperature values. Average inlet temperature of the waste water discharged from dyeing plant can be calculated as

$$T_{ww,in} = \frac{\sum_{i=1}^{n} \dot{m}_i C p_i T_i}{\sum_{i=1}^{n} \dot{m}_i C p_i} \quad (11)$$

Economical profit (EP) of the WHRS can also be expressed as the price of the equivalent natural-gas rate to the recovered heat transfer. Economical profit is calculated based on the rate of recovered heat transfer. Natural-gas price (NGP) is taken as 0.2512 \$/m^3 [47].

$$\text{EP} = (\text{Mass flow rate of natural-gas}) \times \text{NGP} \quad (12)$$

Taal et al. [48] compared different methods of cost estimation for heat exchangers. Cost of cross-flow and multi-pass shell and tube type heat exchanger with multiple passes of the tube bundles for stainless steel material can be calculated from Eq. (13) according to heat exchanger surface area, A_s.

$$\text{Cost of Heat Exchanger} = 10{,}000 + 324 A_s^{0.91} \quad (13)$$

Stainless steel is selected as the heat exchanger material because of the corrosive properties of used waste water.

Total cost of the investment is sum of the heat exchanger, installation and auxiliary equipment costs. Cost of pumps, valves, pipes, re-organization of installation area, connections, tests and regulations, transportation, engineering service costs should be taken into consideration for a feasible system. The other costs mentioned above are nearly doubled the cost of heat exchanger alone.

Net cash flows and net benefits are important for the project developers. Net present value, NPV, method is a powerful indicator of the viability of the projects and can be determined from the following equation:

$$\text{NPV} = \sum_{i=1}^{n} (B - C)_i a_i \quad (14)$$

where NPV is the net present value, B is the benefit, C is the cost and "a" is the discount rate. Discount rate, a, can be calculated as

$$a = \frac{1}{(1+i)^p} \quad (15)$$

Table 1
Average values of parameters

Process	Process time, t (min)	Temperature, T (°C)	Volume, V (L)
1. Bleaching	30	96	5000
2. Washing	20	96	5000
3. Acidification	10	50	5000
4. Dyeing	60	96	5000
5. Cold rinsing	10	30	5000
6. Washing	20	90	5000
7. Hot rinsing	10	70	5000
8. Finishing	20	40	5000

Table 2
Results of the thermodynamic analysis (one shell—four passes heat exchanger)

Parameter	Quantity	Unit
Heat transfer capacity, Q	2020	kW
Heat transfer surface area, A_s	228.4	m^2
Effectiveness, ε	0.92	–
Exergy destruction rate, $\dot{I}$	76.35	kW
Entropy generation rate, S_{gen}	0.265	kW/K
Second law efficiency, η_{II}	0.667	–
Total cost of the WHRS	110773	\$
Annual economical profit, EP	423837	\$/year

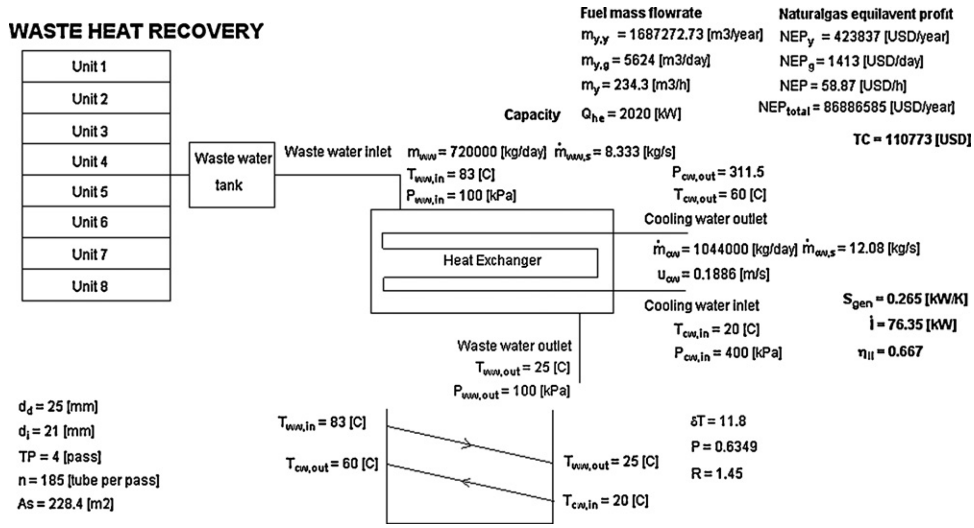


Fig. 1. Schematic illustration of WHRS.

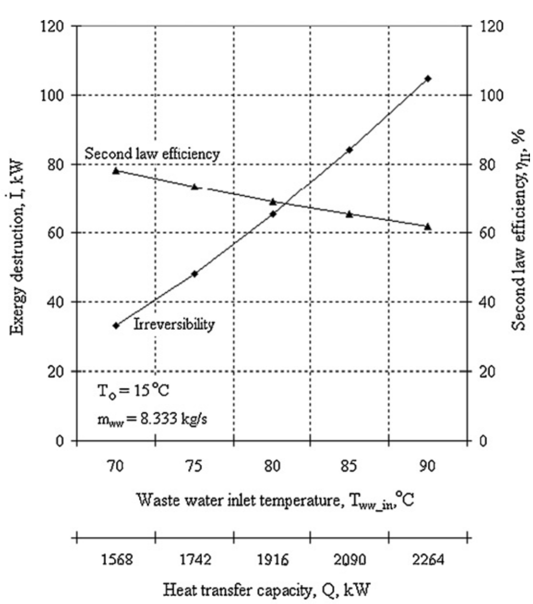
where i is the interest rate and p is the period of month. Tables 2 and 3 are shown the results of the technical and economical analysis of the case study, respectively.

It is clearly observed from Tables 2 and 3 that the NPV is reached positive value in 4 months i.e. payback period, PBP, is about 4 months and therefore the investment seems to be very feasible. According to data of Bursa Chamber of Commerce and Industry, there are 205 active dyeing plants in Bursa. So, the total economical value of waste-heat is easily calculated as approximately 87,000,000 \$/year in Bursa.

4. Parametric study and discussion

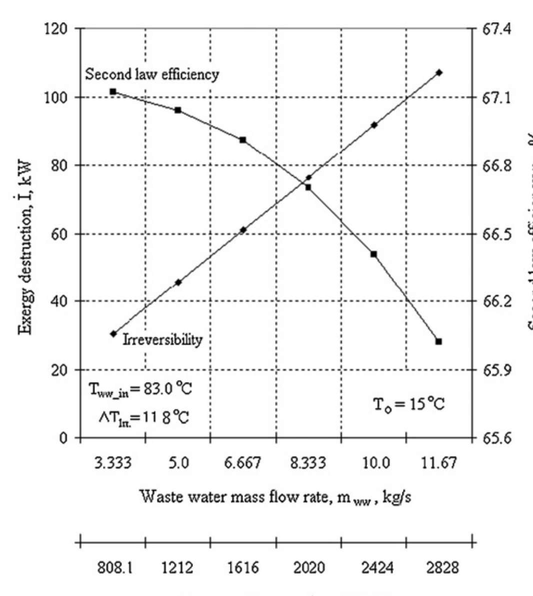
Performance of WHRS strongly depends on the thermo-physical conditions of the waste water. Therefore, the determination of the most convenient working condition is important to maximize the efficiency and minimize the PBP for a specified waste-heat source. It may be challenging to find suitable working conditions among a lot of options. The present study can be also used to predict the effects of many parameters on the performance of WHRS. These parameters include the operation conditions of the WHRS, such as the waste-water inlet temperature, cooling-water inlet pressure, mass flow rate of the waste water and dead state conditions.

Fig. 2 shows the variation of the exergy destruction rate, second law efficiency, economical profit, heat transfer capacity versus different waste-water inlet temperature at same mass flow-rate. Mass flow rate of the waste water was kept constant as 8.333 kg/s for this part of the analysis to investigate the effect of inlet temperature. For this reason, the mass flow-rate of



m_{cw} (kg/s)	9.375	10.42	11.46	12.5	13.54
Effectiveness (%)	90	90.91	91.67	92.31	92.86
Economical Profit (\$/year)	328839	365377	401914	438452	474990

Fig. 2. Variation of $\dot{I}$, η_{II} with waste-water inlet temperature.



m_{cw} (kg/s)	4.833	7.25	9.667	12.08	14.5	16.92
Economical Profit (\$/year)	169535	254302	339070	423337	508604	593372

Fig. 3. The evaluation of waste-water mass flow rate.

Table 3
Results of the economical analysis (NPV)

Months, p	0	1	2	3	4
Initial investment cost	−110773				
Benefit per month, B		35319.75	35319.75	35319.75	35319.75
Maintenance and repair costs		−400	−400	−400	−400
Operation cost for pumps[a]		−610	−610	−610	−610
Net cash flow	−110773	34309.75	34309.75	34309.75	34309.75
Discount rate, a[b]	1	0.980392	0.961169	0.94232233	0.923845
Discounted net cash flow	−110773	33637.01	32977.46	32330.8437	31696.91
NPV		−77136	−44158.5	−11827.686	19869.22

[a] Electricity price: 0.1016 \$/(kW h).
[b] Interest rate: $i = 2\%$.

cooling water is recalculated for each different temperature cases. In addition, Fig. 2 also shows the variation of the mass flow rates of the cooling water according to different waste-water inlet temperature at constant waste-water mass flow rate.

Increasing of waste-water inlet temperature from 70 to 90 °C the second law efficiency decreases nearly 21%. On the other hand, as expected, EP and Q are increased up by increasing the inlet temperature. Economical profit, EP, is dependent upon the recovered heat transfer directly. So, the economical profit is increased by increasing the recovered heat transfer. On the other hand, exergy destruction, I, is re-calculated for different inlet temperatures. It can also be seen from Fig. 2, the magnitude of the exergy destruction rate is clearly depending on inlet temperature. Exergy destruction, I, occurs as a result of heat transfer at finite-temperature difference. Exergy is consumed during the process due to irreversibilities, so, the increased temperature is proved bigger exergy destruction.

The effect of waste-water mass flow rate on the WHRS parameters can be seen in Fig. 3. In order to investigate the effect of mass flow rate of waste water, inlet temperature is kept constant as 83 °C and energy balance in heat exchanger is rewritten for determining the cooling water mass flow rate. Fig. 3 indicates that the exergy destruction rates increases by increasing the $\dot{m}_{ww}$ values at constant log-mean temperature. As expected that the lesser mass flow rate is implied that lesser heat transfer capacity and annual economical profit.

Plots of the exergy destruction rate versus the cooling water inlet pressure are shown for different waste-water inlet temperatures in Fig. 4. The results show that the high exergy destruction rates are obtained at low inlet pressures at same waste-water inlet temperature. In general, when the inlet pressure is increased from 200 to 800 kPa, the exergy destruction rate is decreased for all constant inlet temperature cases. On the other hand, higher exergy destruction rate is obtained for the conditions of fixed inlet pressure and higher T_{ww_in} values. For example, exergy destruction rate is decreased 46% while the waste-water inlet temperature decreasing from 90 to 75 °C at 200 kPa.

Maximum possible work of a system at a specified state depends on dead state (environment) conditions as well as the thermo-physical properties of the system. In other words, the exergy is a property for both system and its surroundings combinations. To investigate of the effects of dead state temperature on WHRS, an analysis is carried out at same

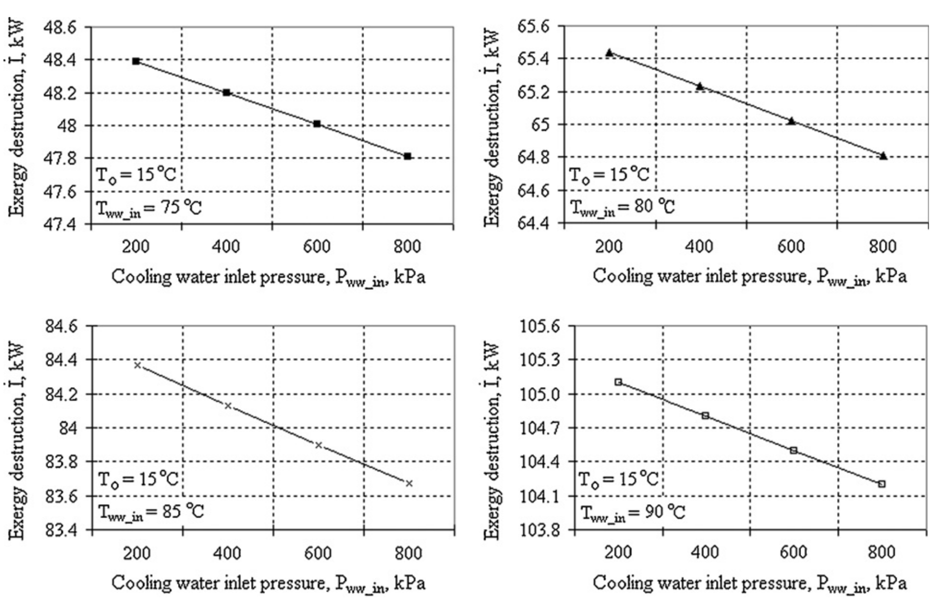


Fig. 4. Exergy destruction rates for inlet pressure values.

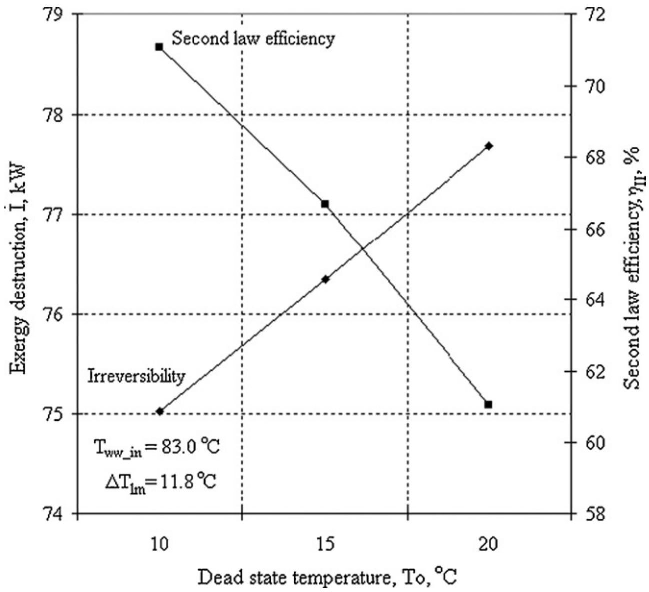


Fig. 5. Evaluation of effect of dead state temperature.

environmental pressure and fixed waste-water inlet temperature. The variation of exergy destruction rate and second law efficiency with dead state temperature is shown in Fig. 5. Results obtained from the analysis represent the second law efficiency decreases with the increasing of dead state temperature at constant log-mean temperature in Fig. 5.

5. Conclusions

High performance in production has turned into a major issue for Turkish textile industry because of the competition in all over the world. Economy is vitally significant in applying energy recovery projects. The economics of the heat recovery application was discussed, and useful results were investigated for a sample problem in Bursa. The present formulation seems to be helpful, especially for industrial applications which have high energy saving potential.

The first law of thermodynamics analysis is still the most commonly used method in the analysis of thermal systems. However, the first law is only related with the conservation of energy, and it gives no information about how, where, and how much the system performance is degraded. On the contrary, the second law of thermodynamic is a powerful tool for the design, optimization and performance evaluation of the thermal systems. In recent years, there has been a growing interest in the use of the principles of the second law of thermodynamics for analyzing and evaluating the thermodynamic performance of thermal systems as well as their technologies. So, in the present study, a thermodynamic and economical analysis were performed for optimizing and describing the effective working conditions for WHRSs. Based on the present analysis, the following results were concluded:

1. Waste-heat recovery techniques which are environmental friendly and have technical and economical advantageous should be evaluated in order to contribute to energy economy studies in Turkey and similar developing countries.
2. The payback period was determined less than 6 months for investigated WHRS.
3. Maximum useful work or exergy is a much stronger criterion for the evaluation of the WHRSs like other thermal systems. Applying of the second law of thermodynamics to WHRSs is a consistent base for determining system efficiency and reliability. These results give a better understanding of application of waste-heat sources for both academic and industrial users. Analysis based on the second law of thermodynamics is a strong and consistent tool for application, usage and development ideas for WHRSs.
4. The results of the thermo-economical analysis show that the exergy destruction rate and economical profit increase with increasing of mass flow rate of the waste water. Similarly, exergy destruction rate, effectiveness and economical profit increase while the second law efficiency decreases as the waste-water inlet temperature increases. Finally, obtained results represent the second law efficiency decreases with the increasing of dead state temperature.
5. The results of the thermo-economical analysis were given for both academic and industrial users. Also optimum parameters presented here are simple and have wide applicability.
6. Similar approach can be carried out on automotive and other industries as well.
7. It is also recommended that future research should be carried out in close co-operation with industry.

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